

# Sky Brightness Analysis using a Million Ground-Based Electro-Optical Deep Space Surveillance (GEODSS) Observations

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## CONFERENCE PAPER

Brightness of the sky background due to lunar phase and location can dramatically affect the limiting magnitude of astronomical detectors. Formerly, theoretical models have attained limited data sets with 10-20% differences between model and observation. This paper compares and contrasts previous investigations with over a million data points collected from various GEODSS sites located around the world, and attempts to refine predictive modeling of sky brightness for use in scheduling, as well as modeling and simulation tools.

## 1. INTRODUCTION

In this paper we analyze a vast number of sky brightness observations from the United States Air Force's three Ground-Based Electro-Optical Deep Space Surveillance (GEODSS) sites with the goal of increasing the fidelity of our modeling and simulation software. The GEODSS system is comprised of three facilities located in Socorro, New Mexico; Maui, Hawaii; and Diego Garcia, British Indian Ocean Territory. Each GEODSS telescope uses a 1 meter primary mirror and highly sensitive digital camera known as Deep STARE.[1] The data available to us for this study includes nearly a million data points each with date and time of observation, measured sky brightness at the sky location of observation, and atmospheric extinction coefficient. From the date and time for each observation we determine the phase and location of the moon relative to the observation. For this report we are specifically interested in determining the change in the visual magnitude of background dark sky based on the relative position and phase of the moon. Reasonably straight forward physics based algorithms have been presented in the literature by Krisciunas and Schaefer with a reported 23% accuracy.[4] With our large statistical sampling we endeavor to improve the fit of these equations to our data by adding a bias factor to one of our measured parameters.

## 2. BACKGROUND

The following equation, as derived by Krisciunas and Schaefer, represents the change in visual magnitude caused by contributions of scattered moonlight[4]:

$$\Delta V = -2.5 \log[(B_{moon} + B_0(Z))/B_0(Z)], \quad (1)$$

where

$$B_0(Z) = B_{zen} 10^{-0.4k(X-1)} X, \quad (2)$$

$$B_{moon} = f(\rho) I^* 10^{-0.4kX(Z_m)} [1 - 10^{-0.4kX(Z)}], \quad (3)$$

$$I^* = 10^{-0.4(3.84+0.026|\alpha|+4 \times 10^{-9}\alpha)}, \quad (4)$$

$$f(\rho) = 10^{5.36} [1.06 + \cos^2(\rho)] + 10^{6.15-\rho/40}, \quad (5)$$

$$X(Z) = (1 - 0.96 \sin^2 Z)^{-0.5}. \quad (6)$$

The input parameters required for these equations are lunar phase angle  $\alpha$ , moon/sky separation  $\rho$ , extinction coefficient  $k$ , zenith distance of the moon  $Z_m$ , and zenith distance of the sky position  $Z$ . The only value

Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE <b>SEP 2012</b>		2. REPORT TYPE		3. DATES COVERED <b>00-00-2012 to 00-00-2012</b>	
4. TITLE AND SUBTITLE <b>Sky Brightness Analysis using a Million Ground-Based Electro-Optical Deep Space Surveillance (GEODSS) Observations</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>The MITRE Corporation, 202 Burlington Road, Bedford, MA, 01730-1420</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES <b>In Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS), 11-14 Sep 2012, Maui, HI.</b>					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Same as Report (SAR)</b>	18. NUMBER OF PAGES <b>5</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

required for calculating  $\Delta V$  that we do not get directly from our data is the dark zenith sky brightness  $B_{zen}$ . To convert between linear brightness values ( $B$ ) in nanoLamberts and logarithmic visual magnitudes per square arc second ( $V$ ) we use[2]

$$B = 34.08e^{(20.7233-0.92104V)}. \quad (7)$$

In the following section we discuss the processing of our data and compare the theoretical values predicted by Eqn. 1 and our measured data. Additionally we discuss a modification we make to reduce the error between the predicted and measured values which gives us better agreement between our simulations and measured data.

### 3. RESULTS/DISCUSSION

GEODSS sites operate during twilight to maximize data collection time. For our analysis the data collected during twilight has added background brightness that we are not accounting for in this analysis so we choose to remove this data. Data from the Maui site collected over a 10 day period is shown in Fig. 1. We manually remove the twilight data as indicated in the figure.

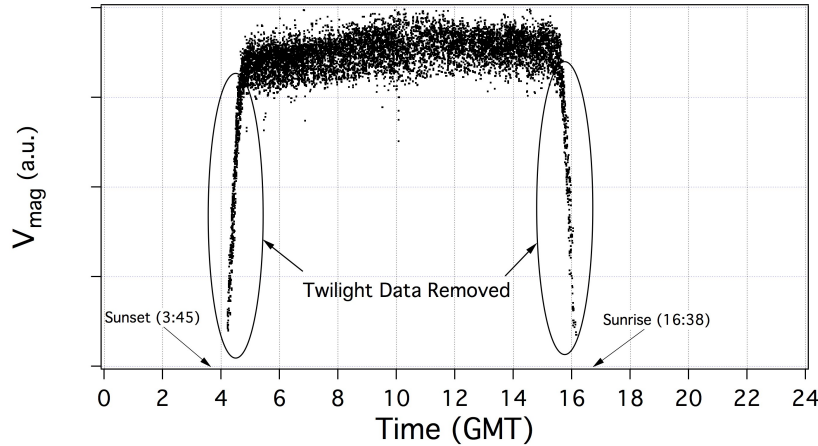
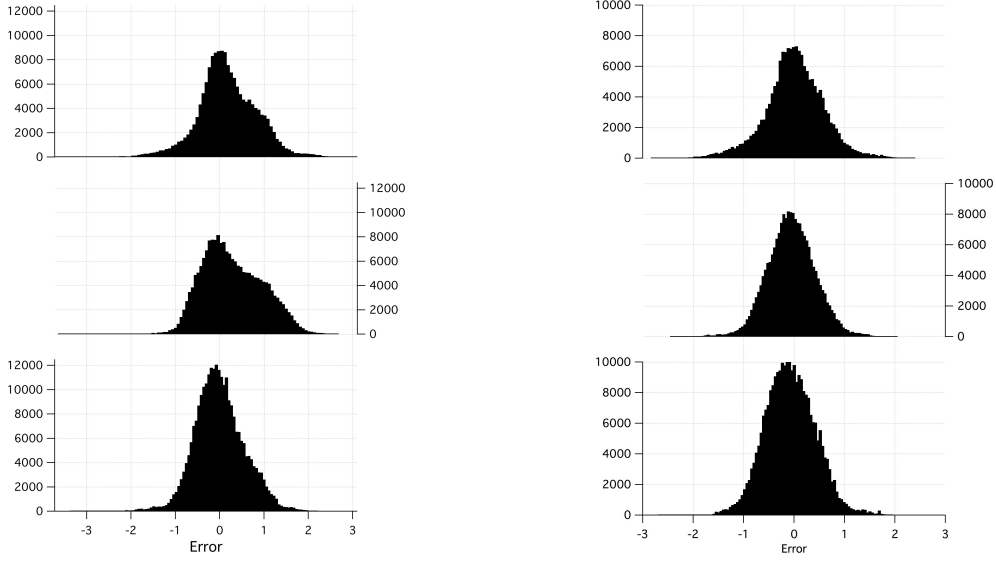


Figure 1: Data acquired by the Maui GEODSS site over a ten day period. Local sunrise and sunset are indicated on the graph. Twilight data that is circled was removed for the analysis presented in this paper.

Once the twilight data is removed we separate out the data for each site collected when there is no moon in the sky. We use this “moonless” data to calculate a median dark sky visual magnitude. The value for the dark sky visual magnitude for each site is used in Eqn. 7 to find  $B_{zen}$ . We then use Matlab<sup>®</sup> to perform an optimized fit for  $\Delta V$ . The optimization algorithm we use minimizes the mean squared error (MSE). The histograms for the errors for each of the GEODSS sites is shown in Fig. 2a. The value for MSE for Socorro, Maui, and Diego Garcia is 0.324, 0.518, and 0.462 respectively. The asymmetric nature of these histograms is an indication that we may not be accounting for one or more systematic sources of error. We acknowledge that we are not accounting for some sources of sky brightness to include galactic latitude[5] of our observation as well as fluctuations in solar brightness[3].

In an attempt to keep our modeling and simulation algorithms relatively simple we choose to apply an empirical bias factor to  $B_{zen}$  as opposed to using more complicated algorithms that take secondary effects such as galactic latitude and solar activity level into account. In doing this we break the connection between  $V$  and  $B_{zen}$  given by Eqn. 7. When we allow these two variables to be optimized independently by the fitting function we arrive at a fit that is an average of 32% better. The most significant change is for the data from Maui which is more than 50% better according to this metric. The new MSE values are 0.268, 0.240, and 0.344 for Socorro, Maui, and Diego Garcia respectively. The fitting results are shown in Table 1. The columns labeled  $V$ ,  $B_{zen}$  and MSE are the results from directly using Eqns. 1-6 whereas the last two columns



(a) The fitting parameter for this set of histograms is the dark zenith sky brightness  $B_{zen}$ . (b) The fitting parameters for this set of histograms are the dark zenith sky brightness  $B_{zen}$  and  $\Delta V$ .

Figure 2: Histograms of the error between theory and data for the three GEODSS sites located at Socorro, NM; Maui, Hawaii; Diego Garcia from top to bottom respectively in each figure.

represent the values where we allow  $B_{zen}$  to vary independently from  $V$ . We call these new values  $B_{zen}^*$  and  $MSE^*$ . For completeness we include the average extinction coefficient  $k$  from our data which we used for these fits. Using this two parameter fitting approach, we arrive at a fairly simple empirical equation that

Table 1: Fitting Parameters

Site	$k$	$V$	$B_{zen}$	MSE	$B_{zen}^*$	$MSE^*$
Socorro	0.60	21.11	122.59	0.324	165.82	0.268
Maui	0.54	21.35	98.28	0.518	224.18	0.240
Diego Garcia	0.34	21.10	123.73	0.462	199.89	0.344

can be used in our modeling and simulation work. The blue dots shown in Fig. 3 are calculated using this equation, while the black dots represent measured data from the Socorro GEODSS site. The ten subfigures show the value of  $\Delta V$  for different lunar phases. The data and fits from Maui and Diego Garcia show similar agreement.

## 4. CONCLUSION

In conclusion we feel that by using Krisciunas' and Schaefer's equations with the addition of a small bias factor for  $B_{zen}$ , we achieve nice agreement between predictions and measured data for the brightness of the night sky as a function of lunar phase and location. The addition of this algorithm to our modeling and simulation software allows us to further enhance the fidelity of our results.

We would like to thank the Electronics Systems Center's HSIJ program office and the Executive Agent for Space (EA4S) for continued support of our modeling and simulations efforts.

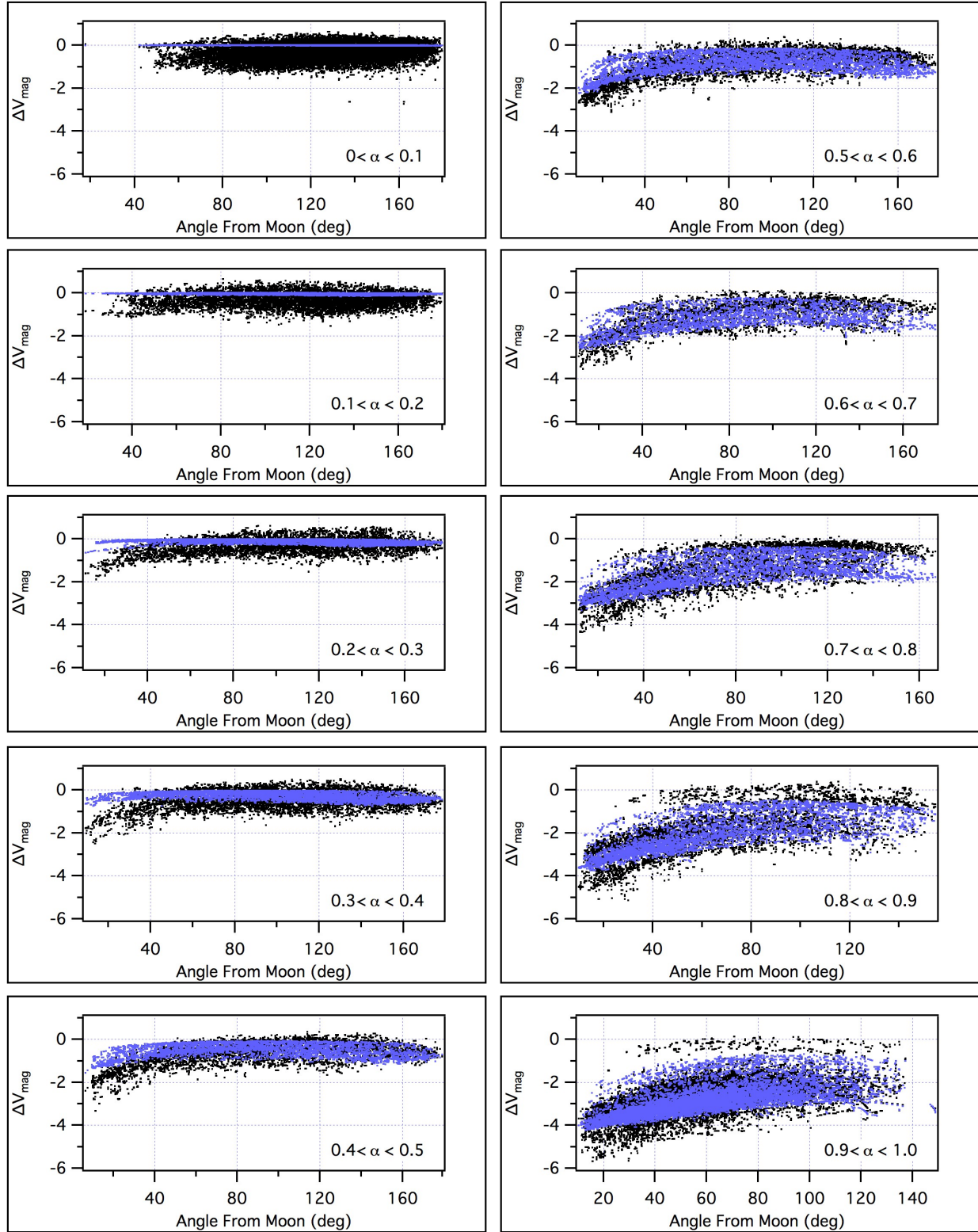


Figure 3: Comparison of simulated results and data collected from the Socorro, NM GEODSS site. Each subfigure shows a different moon phase  $\alpha$ .

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